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Complex Plasmas Liquid Crystal

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Abstract

Ordered structures of rodlike (cylindrical) particles in dc and rf gas discharge plasmas were investigated. It was shown theoretically and observed experimentally that only two orientations (parallel and perpendicular to the external electric field) of cylindrical particles are possible, and that changing of discharge parameters can result in changing of the particle orientation.

Most of the experimental and theoretical works dealing with the investigation of complex (dusty) plasmas were performed with spherical particles. On the other hand, it is well known that colloidal dispersions, which have much in common with complex plasmas, show a much broader spectrum of possible states in the case of cylindrical or disk particles. In colloidal dispersions, liquid phase as well as several liquid-crystal and crystal phases with different degrees of orientational and positional ordering can be observed. It is also well known that the use of cylindrical probes (in addition to spherical) considerably broadens the possibilities of low--temperature plasma diagnostics. It is therefore obvious that the use of cylindrical particles can considerably broaden the frontiers of complex plasma research.

In an experiment by Molotkov *et al.* [1] nylon particles of length 300 μm and diameters 7.5 and 15 μm, as well as particles of lengths 300 or 600 μm and diameter 10 μm, were introduced into the plasma of a dc discharge. The discharge operated in neon or neon-hydrogen mixture in the pressure range between 10 and 250 Pa. The discharge current varied from 0.1 to 10 mA. In this parameter range, standing striations were formed in the discharge, which made the particle levitation possible. Particles formed extended structures in the vertical direction. In Fig. 1 a part of a horizontal cross section of an ordered structure levitating in a discharge with 1:1 neon-hydrogen mixture is shown. The observed structures formed by microcylinders revealed clear ordering. Microcylinders formed a horizontal monolayer and were oriented in a certain direction. One could expect that their orientation should be determined by the cylindrical symmetry of the discharge tube. However, no correlation between the particle orientation and discharge tube symmetry was found. Presumably, the preferential orientation was related to a weak asymmetry in the discharge.

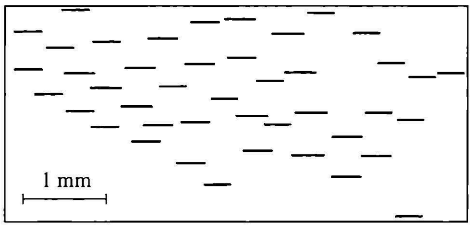

Fig. 1. Digital image of a part of a horizontal section of a structure formed by cylindrical macroparticles of length 300 μm and diameter 15 μm levitating in a striation of a dc discharge in a neon-hydrogen mixture at a pressure of 120 Pa and discharge current 3.8 mA.

Levitation of cylindrical particles was also observed near the sheath edge of a capacitively coupled rf discharge by Annaratone *et al* [2]. In this experiment, cylindrical particles of 300 μm in length and 7.5 or 15 μm in diameter were used, and a small fraction of very long particles (up to 800 μm in length and 7.5 μm in diameter) was also present. A typical picture of a structure formed by these particles is shown in Fig. 2. Longer particles were oriented horizontally, while shorter particles were oriented vertically along the electric field.

Let us consider levitation of a micro-rod of mass m and charge Q suspended in the electric field E of the rf discharge sheath. Parameters of the equilibrium state of the particle (the vertical coordinate of its center of mass h_0 and the orientation angle a_0 with respect to the vertical axis) can be found from minimization of the potential energy of the particle $U(h;a)$. We now assume that among the different forces that act on the suspended micro-rods the electric force is dominant. Interaction between particles can be ignored in low particle density structures when the Debye length is shorter than all the other distances involved. Assuming for simplicity that the particle charge does not depend on h and a, the potential energy is determined by the following expansion:

$$U(h,\alpha) \cong mgh + Q\phi(h) - \frac{dE(h)}{2}\cos^2\alpha - \frac{dE(h)}{2}\cos^2\alpha - \frac{DE'(h)}{12}(3\cos^2\alpha - 1) + \ldots \quad (1)$$

with $E < 0$ and $E' > 0$. The magnitudes of the dipole and quadrupole moments are $d \approx EL^3/24\Lambda < 0$ and $D \approx QL^2/6 < 0$, respectively [here $\Lambda = \ln(L/a)$ with the rod length L and radius a]. Equation (1) is obtained in the approximation of a "weakly inhomogeneous" field. [$\ell_E = |E_0/E_0'| >> L$, where $E(h) \approx E(h_0) + E'(h_0)(h - h_0)$] for particles with high aspect ratio, $L/a >> 1$. The equilibrium state of particles is determined by the absolute minimum of the potential energy. The conditions $\partial U/\partial h = 0$ (force balance) and $\partial U/\partial\alpha = 0$ (torque balance) result in

$$mg \cong QE_0 + dE_0'\cos^2\alpha, \quad \left(\frac{E_0^2 L}{2\Lambda} + QE_0'\right)\sin 2\alpha = 0 \cdot \quad (2)$$

The first equation shows that in addition to the gravity and monopole electric forces, the dipole force contributes to the balance condition in vertical direction. However, this force does not affect the balance noticeably. From the second equation it follows that only two equilibrium orientation, vertical ($a_0 = 0$) and horizontal ($a_0 = \pi/2$), are possible. The condition for the stable angle one can get from the second derivative of the potential energy:

$$\partial^2 U/\partial\alpha^2 \sim (K-1)\cos 2\alpha_0 > 0, \quad (3)$$

where K is the "orientational parameter",

$$K = \frac{2d\ell_E}{D} \equiv \left(\frac{e|E_0|L}{\gamma_r T_e}\right)\frac{\ell_e}{L}, \quad (4)$$

and

$$\gamma_r = \frac{2\Lambda e|Q|}{LT_e} \quad (5)$$

is the absolute value of the dimensionless particle potential. This shows that the equilibrium is determined by the competition between the dipole and quadrupole terms in Eq. (1). The dipole torque turns the rod along the electric field, whereas the quadrupole torque tends to make it horizontal. Hence, particles levitate horizontally (a_0 $=\pi/2$) when $K < 1$, and vertically ($a_0 = 0$) when $K > 1$. It follows from the obtained solutions that rotation of the rodlike particles in the vertical plane is impossible (it was never observed experimentally either).

Transition between the vertical and horizontal orientations occurs when the ratio $(d{\cdot}l_E)/D$ becomes comparable to unity. The effect of plasma parameters on the orientation was investigated experimentally by Annaratone *et al* [4]. With a driving peak-to-peak voltage on the lower electrode V_{pp} = 430 V, the 600 μm micro-rods injected in an rf plasma levitated vertically for pressures below 60 Pa (Fig. 3a). For pressures below 22 Pa, they formed two or even three layers before falling down to the electrode at a pressures of about 15 Pa. At 60 Pa there is a co-existence of vertical and horizontal orientations (Fig. 3b), and for higher pressure the particles are normally horizontal (Fig. 3c). The observed orientational changes are in good agreement with the theoretical model of Ref. [3].

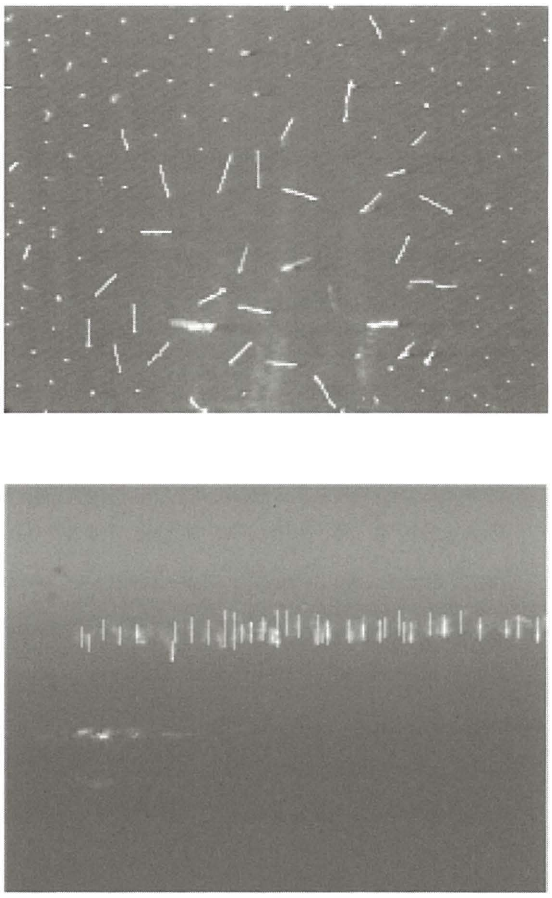

Fig. 2. Typical video images of structures formed by cylindrical particles levitating near the sheath edge of an rf electrode. The discharge operated in krypton at a pressure of 52 Pa and discharge power of 80 W. Left panel shows a top view, dots correspond to vertically oriented particles; right panel represents a side view.

Fig. 3. Levitation of the nylon particles of length 600 μm and diameter 5 μm above an rf electrode driven at the peak-to-peak voltage V_{pp} = 430 V: (a) at a pressure of 32 Pa (dc bias = 124 V); (b) at 60 Pa (dc bias = 95 V); (c) at 98 Pa (dc bias = 82 V).

REFERENCES

[1] V. I Molotkov, A. P. Nefedov, M. Y. Pustyl'nik, V. M. Torchinsky, V. E. Fortov, A. G. Khrapak, and K. Yoshino, “Liquid plasma crystal: Coulomb crystallization of cylindrical macroscopic g

[2] rains in a gas-discharge plasma”, JETP Lett. **71**, 102-105 (2000)

[3] B. M. Annaratone, A. G. Khrapak, A. V. Ivlev, G. Söllner, P. Bryant, R. Sütterlin, U. Konopka, K. Yoshino, M. Zuzic, H. M. Thomas, and G. E. Morfill, “Levitation of cylindrical particles in the sheath of rf plasma”, Phys. Rev. E **63**, 036406/1-6 (2001)

[4] A. V. Ivlev, A. G. Khrapak, S. A. Khrapak, B. M. Annaratone, G. Morfill, and K. Yoshino, “Rodlike particles in gas discharge plasmas: Theoretical model”, Phys. Rev. E **68**, 026403/1-10 (2003)

[5] B. M. Annaratone, A. G. Khrapak, and G. E. Morfill, “Peculiar properties of rodlike particles levitating in the sheath of an rf plasma”, IEEE Plasma Phys. **37**, 1110-1115 (2009)